# APPLICATION FOR UNITED STATES

# LETTERS PATENT

## CONTROL OF LINER THICKNESS FOR IMPROVING THERMAL CYCLE RELIABILITY

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# CONTROL OF LINER THICKNESS FOR IMPROVING THERMAL CYCLE RELIABILITY

## BACKGROUND OF THE INVENTION

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### 1. Field of the Invention

The present invention relates to semiconductor processing, and more particularly to a system and method for employing feature characteristics, such as, liner

10    thickness as an indicator of thermal stress during temperature cycles in metal structures.

### 2. Description of the Related Art

Reliability under thermal cycle conditions is one of

15    the main concerns when integrating Back End of Line (BEOL) structures with low dielectric constant dielectrics. The cause of thermal cycle fails is typically the mismatch in the coefficients of thermal expansion (CTE) between the metallization and the surrounding insulator. For example,

20    the CTE of copper (Cu) is approximately 16 ppm/$^{\circ}$C while that of SiLK™ (trademark of Dow Chemical) is approximately 60

ppm/$^\circ$C.  As a result, the Cu metallization is strained

during thermal cycle testing, which can lead to crack

formation in Cu vias and eventual failure.  While the

thermal cycle performance of a given process can be

5    evaluated by stressing specifically designed test

structures, such as stacked via chains, this can only be

done on a limited sampling of parts and only on complete

builds of the structure.

It would be highly desirable to have a method and

10   apparatus for determining the thermal cycle performance

provided by a manufacturing process before completing

manufacturing of the device.


## SUMMARY OF THE INVENTION

15   A system, apparatus and method for evaluating

reliability of a semiconductor chip are disclosed.  Strain

is determined at a location of interest in a structure.

Failures are evaluated in a plurality of the structures

after stress cycling to determine a strain threshold with

20   respect to a feature characteristic.  Structures on a chip

or chips are evaluated based on the feature characteristic

to predict reliability based on the strain threshold and

the feature characteristic.  Predictions and design changes

may be made based on the results.

5          A semiconductor device includes a metallization

structure having a metal patterned with conductive liners

along bottoms and sidewalls of vias of the structure.  A

dielectric material surrounds the metal, wherein a mismatch

in coefficient of thermal expansion (CTE) exists between

10     the metallization and surrounding insulator.  The

conductive liners are configured and dimensioned to provide

a liner thickness that makes the metallization structure

less susceptible to thermal cycle failure such that no

failures are expected during thermal cycle stress

15     conditions, e.g., during -65 °C to +150 °C cycles.

These and other objects, features and advantages of

the present invention will become apparent from the

following detailed description of illustrative embodiments

thereof, which is to be read in connection with the

20     accompanying drawings.

## BRIEF DESCRIPTION OF DRAWINGS

The invention will be described in detail in the following description of preferred embodiments with reference to the following figures wherein:

FIG. 1 is a schematic cross-sectional view of a test structure in accordance with one embodiment of the present invention;

FIG. 2 is a log-log plot of $N_{50}$ versus average resistance on a test device for different lots tested after thermal cycle testing in accordance with one embodiment of the present invention;

FIG. 3 is a log-log plot of $N_{50}$ versus liner thickness for the phase A and phase B liner processes in accordance with the present invention;

FIG. 4 is a plot of predicted strain at via bottom versus liner thickness for Cu metallization in accordance with the present invention;

FIG. 5 is a plot of predicted strain at via bottom versus liner thickness for Cu metallization and a high

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coefficient of thermal expansion (CTE) dielectric showing different elastic properties of the liner in accordance with an embodiment of the present invention;

FIG. 6 is a plot of predicted strain at via bottom versus liner thickness for Al metallization and a high CTE dielectric showing different elastic properties of the liner in accordance with an embodiment of the present invention;

FIG. 7 is a plot of predicted strain at via bottom versus liner thickness for Cu metallization and a medium CTE dielectric showing different elastic properties of the liner in accordance with an embodiment of the present invention;

FIG. 8 is a plot of predicted strain at via bottom versus liner thickness for Al metallization and a medium CTE dielectric showing different elastic properties of the liner in accordance with an embodiment of the present invention; and

FIG. 9 is a block/flow diagram showing steps for predicting reliability based on feature characteristics of a device in accordance with the present invention.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The present invention relates to determining reliability of a semiconductor device.  In particularly useful embodiments, the present invention employs physical attributes of a chip to indicate the reliability of a device.   In one embodiment, liner thickness of interconnects (between layers in a chip structure), for example, Dual Damascene interconnects, is employed as a parameter that directly correlates with the thermal cycle reliability of via stacks during thermal cycling.  A Dual Damascene process is commonly employed for fabricating metal interconnects.

The liner thickness of, e.g., Dual Damascene

interconnects may be used as a measure of the thermal cycle

performance.  This can be used to control the thermal cycle

behavior of back end of line (BEOL) structures.

5      Measurement of, for example, liner thickness provides a

sensitive way to determine when process conditions fall

outside a desirable window, where the process window

assures thermal cycle reliability during the manufacture of

BEOL structures.

10      Referring now in detail to the figures in which like

numerals represent the same or similar elements and

initially to FIG. 1, a schematic cross section of a

structure 10 used for thermal cycle study in accordance

with one embodiment of the present invention is shown.  The

15   test structure 10 (also referred to as a "stacked via

chain") is employed to verify the stability of, e.g.,

SiLK™/Cu BEOL structures during thermal cycling.  It should

be noted that other metals and dielectric materials may be

employed in addition to or instead of the SiLK™/Cu

20   materials illustratively described herein.  For example

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dielectrics such as SiCOH, nitrides, silicon dioxide or other organic or inorganic dielectrics may be employed. In addition, metals such as aluminum (Al), copper (Cu), Gold (Au), silver (Ag), and alloys or combinations thereof may

5    also be employed.

The structure 10 includes a stacked via chain 12, where two SiLK™ levels 14 (e.g., levels M2/V1, and M1/CA) are followed by two silicon dioxide (SiO$_2$) levels 16. The chain 12 may include, e.g., 50 links, alternating between

10   layer MC, which may include a tungsten (W) local interconnect 18, and M2. Other numbers of links and configurations are also contemplated.

Structure 10 preferably includes a dual damascene structure to provide stress risers at the interface between

15   vias 22 (CA and V1) and adjacent metal. Other structures that can fail due to thermal induced strain may also be employed.

M1 may include a square plate 20. In one example, plate 20 measures about 0.35 μm on a side while CA and V1

20   measure about 0.22 μm in diameter.

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Thermal cycle failure is a result of metal fatigue, a phenomenon described by crack formation and growth due to cyclic strain. During thermal cycle testing, layers 14 (e.g., SiLK™) expand and contract significantly, generating

5    large stresses in vias 22 (e.g., CA and V1). The resulting via strain is enhanced by the mechanical confinement of the rigid $SiO_2$ layers above (16) and below (24) the metallization. Layers 24, in this case, are formed on a substrate 8, which may include, for example, a silicon or

10   silicon-on-insulator material. Eventually, cracks may be initiated in regions 26 and propagate across the vias 22 (e.g., formed from Cu), causing a resistance increase if the cracks reach a critical size. An electrical open occurs if the cracks compromise liner integrity for liners

15   27 formed on sides and bottoms of vias 22.

In one embodiment, the structure 10 includes aluminum (Al), copper (Cu), Gold (Au), silver (Ag), or alloys thereof as metal and, the dielectric may include an organic material, such as SiLK™ or polyimide. A liner material 27

20   may include tantalum (Ta), tantalum nitride (TaN), titanium

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(Ti), titanium nitride (TiN) or tungsten (W). The liner material is deposited prior to filling via holes with metal. The mismatch in CTE between the metal and insulator is preferably greater than about 30 ppm/°C.

5      Test structure 10 may be employed to verify the stability of SiLK™/Cu BEOL structures during thermal cycling.

Referring to FIG. 2, two different processes, Phase A and Phase B are compared such that there is a one to one

10     correspondence between the resistance of the structure (as built) and the failure rate of the structure during thermal cycle testing. FIG. 2 is a log-log plot of $N_{50}$ (the number of cycles to 50% failure) versus Average Resistance for structure 10 for different lots of devices (lots 1-4,

15     indicated respectively by find numerals 204-207 in FIG. 2), which were thermal cycled from -65 °C to +150 °C. The data is fit to an empirical relation, $N_{50}=A(R_c-R)^{-n}$, where $R_c$ is a critical resistance above which thermal cycle fails should not occur. A and n are coefficients determined to

20     provide the best fit for plot 200.

Plot 200 shows strong agreement between a mathematical

model 202, given by the solid line, and actual data

indicated by the shapes indicative of lots 1-4 (204-207).

One concept behind the model is that a higher resistance

5       for structure 10 corresponds to a thicker liner 27 (FIG.

1).  This is due to the liner materials, which may include

tantalum (Ta) and/or tantalum nitride (TaN) that have much

higher resistivities compared to, say, Cu metallization.

The liner 27 may be thought of as sharing the stress in the

10      stacked via structure (e.g., vias 22 in FIG. 1) with the

Cu.  The liner materials may have a higher bulk modulus and

a higher yield stress than Cu or other metals.  Therefore,

a thicker liner 27 corresponds to greater structural

support in the stacked via structure 12.

15      Although there may be other factors that affect the

resistance (grain size, via dimensions), the liner

thickness is the most likely source of differences in

resistance, particularly since process differences, e.g.,

phase B hardware may have a thicker liner than the phase A

20      hardware, are known.  FIG. 2 shows a large difference in

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$N_{50}$ for the two phase B lots (lots 3 and 4) over phase A

lots (lots 1 and 2), which were processed at around the

same time.

To verify that the thermal cycle performance

5      correlates with liner thickness, samples from two of the

lots shown in FIG. 2 were submitted for transmission

electron microscope (TEM) analysis.  The first lot is

indicated by reference number 204, and the second lot is

indicated by reference number 206.  The TEM cross sections

10     of structure 10 from lots 204 and 206 measured approximate

liner thicknesses at various points in the stacked via

structures.  The Phase B liner (lot 206) was clearly

thicker than the Phase A liner (lot 204).  Based on the

measurements of the liner thicknesses, the average liner

15     thickness for lot 204 was 19.42 nm while the average liner

thickness for lot 206 was 25.08 nm.  This information is

employed below.

Referring to FIG. 3, a log-log plot of $N_{50}$ versus

Liner Thickness for lots 204 and 206, clearly shows that a

20     thicker liner with the Phase B process results in a higher

thermal cycle lifetime.

Referring again to FIG. 1, a link or correlation between liner thickness and thermal cycle reliability behavior involves the strain that is applied to the stacked via chain 12 during thermal cycling. The effects of liner thickness are most pronounced at via bottoms in the stacked via structure 10, where the cross-sectional area of the metal (e.g., Cu) is lowest. At this location, the liner 27 acts to carry a larger portion of the force that develops in the stacked via due to the thermal strain.

An evaluation of the elastic strain in the metal (Cu, etc.) can be performed by modeling the mechanical response of the stacked via 12. Expansion of the SiLK™ or other dielectric during an increase in temperature represents the driving force in which the stacked via is stretched between the substrate 8 and the top passivation levels (e.g., layer 16, etc.). The top passivation levels can be modeled as elastic plates on an elastic foundation with pinning forces applied by the stacked via structures 12. The resulting forces on each of the stacked vias 12 are calculated. The

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strain modeling of stacked via structures may be provided

as described in U.S. Patent Application Serial No.

10/726,140, entitled "Building Metal Pillars in a Chip

Structure Support", filed December 2, 2003, which is

5      commonly assigned and incorporated herein by reference.

Because the pinning force is transmitted through all

levels of the stacked via 12, the section with the smallest

cross-sectional area will possess the highest value of

strain.  The results of the strain in the metal (Cu) at the

10     via bottom are illustrated in FIG. 4.

Referring to FIG. 4 with continued reference to FIG.

1, a stacked via, composed of CA/M1/V1/V2 levels, is

subject to a 100 °C increase in temperature with normal

values of via geometry and material properties.  The

15     following illustrative values were employed.  The M1 width

equals about 0.325 $\mu$m, and the M2 width equals about 0.435

$\mu$m.  The CA and V1 vias are tapered such that the diameter

at the via bottom is about 0.230 $\mu$m and the vertical

thickness of CA, M1, V1 and M2 is about 0.320 $\mu$m.  The

20     following values are illustratively employed for the

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elastic modulus, E, of the Cu, liner, SiLK™ and $SiO_2$ layers, and for the CTE, $\alpha$, of the Cu and SiLK™ layers: $E_{Cu}$=130 GPA, $E_{Liner}$=400 GPa, $E_{SiLK}$=3GPa, $E_{oxide}$=70 GPa, $\alpha_{SiLK}$=66 ppm/°C, $\alpha_{Cu}$=16 ppm/°C.

5      As the liner thickness decreases from 40 nm to 20 nm, the strain on the Cu in the via bottom increases from approximately 1.4% to 1.7%.  This change in strain is large enough to affect the $N_{50}$ lifetimes of the stacked via distribution.

10     This model can be extended to other material systems (e.g., liner and metallization composition) and geometries (e.g., liner thickness and via geometry) to assess the expected reliability behavior of future test structures.

The predicted strain at the via bottom versus liner
15     thickness    for    several    combinations    of    materials    is illustratively shown in FIGS. 5-8.

Referring to FIGS. 5-8, predicted strain for a stress condition of -65 °C to +150 °C in which either Cu or aluminum (Al) metallization is used is illustratively
20     shown.    The    results    are    for    a    particular    stacked    via

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geometry, a given taper in the vias, dielectric thickness and oxide passivation thickness.  As such, there are many length scales involved rather than just the radius of the via bottom, so the liner thicknesses applies to a specific configuration.

Referring to FIG. 5, Cu metallization and a high CTE dielectric material, e.g., polyimide or SiLK™ are employed. The results of via strain versus liner thickness are shown for different elastic properties of a liner material.  In the present instance, a liner having the same modulus of elasticity ($E_{Cu}$) as Cu is plotted at curve 302.  A liner having double the modulus of elasticity (2 $E_{Cu}$) of Cu is plotted at curve 304, a liner having triple the modulus of elasticity ($3E_{Cu}$) of Cu is plotted at curve 306.  The temperature difference for thermal cycling was 215 °C with CTE for the dielectric being 66 ppm/°C.

Referring to FIG. 6, Al metallization and a high CTE dielectric material are employed. In the present instance, a liner having 1.5 times the modulus of elasticity (1.5 $E_{Al}$) of Al is plotted at curve 314, a liner having 5 times the

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modulus of elasticity $(5E_{Al})$ of Al is plotted at curve 316. The temperature difference for thermal cycling was 215 °C with CTE for the dielectric being 66 ppm/°C.

Referring to FIGS. 7 and 8, predicted strain for a stress condition of -65 °C to +150 °C in which either Cu or aluminum (Al) metallization is used is illustratively shown. The results are for a particular stacked via geometry, a given taper in the vias, dielectric thickness and oxide passivation thickness. As such, there are many length scales involved rather than just the radius of the via bottom, so the liner thicknesses apply to a specific configuration. FIG. 7 corresponds to Cu metallization and a moderately high CTE dielectric material, e.g., CTE = 30 ppm/°C. The results of via strain versus liner thickness are shown for different elastic properties of a liner material. In the present instance, a liner having the same modulus of elasticity $(E_{Cu})$ as Cu is plotted at curve 322. A liner having double the modulus of elasticity $(2\,E_{Cu})$ of Cu is plotted at curve 324, a liner having triple the modulus of elasticity $(3E_{Cu})$ of Cu is plotted at curve 326.

The temperature difference for thermal cycling was 215 °C with CTE for the dielectric being 30 ppm/°C.

Referring to FIG. 8, Al metallization and a moderately high CTE dielectric material are employed. In the present instance, a liner having 1.5 times the modulus of elasticity (1.5 $E_{Al}$) of Al is plotted at curve 334, a liner having 5 times the modulus of elasticity (5$E_{Al}$) of Al is plotted at curve 336. The temperature difference for thermal cycling was 215 °C with CTE for the dielectric being 30 ppm/°C.

In the case of a low CTE dielectric material (e.g., between about 10ppm/°C and about 20ppm/°C) negligible strain is produced. FIGS. 5-8 list the elastic modulus of the liner as a fraction of that of the metallization (Cu or Al). The cases roughly correspond to the liner materials commonly used for Cu or Al metallization. For example, titanium (Ti) is roughly equivalent to that of Cu, Ta is roughly 2 times higher than Cu, W is roughly 3x higher than Cu, Ti is roughly 1.5 times higher than Al and W is roughly 5x higher than Al.

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In terms of the stress condition, a threshold liner thickness can be determined above which thermal cycle fails should not occur. For example, the industry standard thermal cycle stress condition is -65 °C to +150 °C. This temperature range would correspond to a certain via strain for a given structure and set of materials. Therefore, it is possible to define a threshold via strain that would cause failures if exceeded. In one example, for Cu metallization and a SiLK™ dielectric, where the mismatch in CTE is 50 ppm/°C, the analysis indicates that for a reasonably large sample size of, say, 1000-10000 and a $\Delta T=215$ °C, failures should not be observed after 500 cycles if the via strain is below 2.5% and after 1000 cycles if the via strain is below 2.3%.

The threshold liner thickness for a Ta-based liner would be about 35 nm for 500 cycles and about 45 nm for 1000 cycles under these conditions. Likewise, if the liner is composed of Ti, the threshold liner thicknesses are slightly larger than these values. If the liner is composed of W, the critical liner thickness would be about

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22 nm for 500 cycles and about 28 nm for 1000 cycles. Note that if the CTE of the dielectric is less than 50 ppm/°C, all of the liner materials would not produce fails due to the lower thermal strain.

5      Once determined for a given design, this information may be employed as a reliability measure for chips produced by a given process to provide a given structure. Based on the data gathered, liner thickness can be used to monitor, in place, the thermal cycle reliability of chips during the

10    manufacturing process. This includes measuring the liner thickness from cross sections of a simple kerf structure during the manufacture of the BEOL structure of the chip. Data such as that shown in FIG. 3 would have already been generated for the process by using standard thermal cycle

15    tests.

Similarly, results such as those shown in FIG. 4 can be generated by modeling the mechanical response of various stacked via designs. The liner thickness of the structure could then be used as a direct indicator of thermal cycle

20    performance expected from the process.

Although the results discussed previously apply to Cu

metallization and a SiLK™ dielectric, the same methods can

be applied to other combinations of materials.  For

example, Al metallization can be used instead of Cu and

5          polyimide can be used instead of SiLK™.  The present

invention is particularly useful when a mismatch in CTE

exists between the metallization and surrounding insulator

and that the liner material has a higher modulus compared

to the metal.  However, the concepts and scope of the above

10          disclosure can be applied to other structures, materials

and applications.

It should be understood that the elements shown in

FIG. 9 may be implemented in various forms of hardware,

software or combinations thereof. Preferably, these

15          elements are implemented in software on one or more

appropriately programmed general-purpose digital computers

having a processor and memory and input/output interfaces.

Referring to FIG. 9, a block/flow diagram showing a

system/method for evaluating reliability of a semiconductor

20          chip or chip design is illustratively shown.  In block 500,

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a semiconductor chip design or test structure is provided

having a structure, such as a via structure formed therein.

The via structure may include a liner at an interface

between metal structures and dielectric material or other

5        structure subjected to strain may be employed and benefit

from the present invention.

In block 502, strain (or stress) is determined at

a particular location, for example, at or adjacent to the

liner.  This strain should be determined by calculation,

10       estimate, or measurement.  In block 504, failures may be

induced by thermal cycling in a plurality of the metal

(via) structures to determine a strain threshold for

failures for the design.  The strain threshold is such that

below the threshold no failures occur in the metal

15       structures.

In block 506, this strain threshold is correlated to

characteristics of the liner (or other structure) to create

a metric for which reliability can be determined.  This may

be performed by maintaining statistics on failures and non-

20       failures during the thermal cycling tests on the test

structure(s).

In block 508, reliability of semiconductor chips, which are being made or have already been produced, is predicted based upon measured characteristics of the liner or other structure. Based on initial data, the correlation between, say liner thickness and reliability is made. Therefore, after a chip is manufactured, a sample may have the liner thickness measured to provide a measure of the reliability of that sample to predict electrical or other failures, in block 510. Since a liner may be formed by a uniform deposition process, the liner may be measured at any convenient location of the chip or off the chip (e.g., in the kerf region). In this way, the liner measurement can be made at any time during the manufacturing process and be employed to reject chips prior to their completion. The liner measurement may be made by cross-sectioning and microscope measurement, although other measurement methods may be employed.

In block 512, geometry or materials may be altered in a design to reduce strain and improve reliability of the

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design.  For example, a thickness of a liner may be
increased or decreased or its material changed to affect
the strain.  The greatest benefits of the present invention
are realized for mismatches between the metal structure and
5    the dielectric, which are greater than about 30 ppm/°C.

The present invention provides a metallization
structure that is less susceptible to thermal cycle failure
and includes a metal patterned preferably using a Dual
Damascene process with conductive liners along the bottoms
10   and sidewalls of the vias.  A dielectric material surrounds
the metal, where the mismatch in the coefficient of thermal
expansion (CTE) between the metallization and surrounding
insulator is present along with the liner thickness such
that no failures are expected during a standard -65 °C to
15   +150 °C thermal cycle stress condition.

Some example structures include the following
characteristics.  One structure may include copper (Cu) as
the metal, the liner material may include tantalum (Ta) or
tantalum nitride (TaN). The liner thickness for these
20   materials may be in the range of between about 25nm and

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about35nm, and the CTE of the insulator is in the range of

between about 50ppm/°C and about 75ppm/°C. The tantalum

(Ta) or tantalum nitride (TaN) liner material may include a

thickness in the range of between about 35nm and about

5      45nm, and the CTE of the insulator is in the range of

between about 75ppm/°C and about 100ppm/°C.

In another embodiment, the metal may include copper

(Cu), the liner material may include titanium (Ti) or

titanium nitride (TiN). The liner thickness may be in the

10     range of between about 25nm and about 35nm, and the CTE of

the insulator is in the range of between 50ppm/°C-75ppm/°C.

In another embodiment, the metal includes copper (Cu),

the liner material includes titanium (Ti) or titanium

nitride (TiN), the liner thickness is in the range of

15     between about 35nm and about 55nm, and the CTE of the

insulator is in the range of between about 75ppm/°C and

about 100ppm/°C. In another embodiment, the metal is copper

(Cu), the liner material is tungsten (W), the liner

thickness is in the range of between about 10nm and about

20     20nm, and the CTE of the insulator is in the range of

between about 50ppm/°C and about 75ppm/°C.  In still another

embodiment, the metal includes copper (Cu), the liner

material includes tungsten (W), the liner thickness is in

the range of between about 20nm and about 30nm, and the CTE

5    of the insulator is in the range of between about 75ppm/°C

and about 100ppm/°C.

In other embodiments, the metal includes aluminum

(Al), the liner material includes titanium (Ti) or titanium

nitride (TiN), the liner thickness is in the range of

10    between about 25nm and about 35nm, and the CTE of the

insulator is in the range of between about 50ppm/°C and

about 75ppm/°C.  Further, when the metal includes aluminum

(Al), the liner material includes titanium (Ti) or titanium

nitride (TiN), the liner thickness is in the range of

15    between about 35nm and about 55nm, and the CTE of the

insulator is in the range of between about 75ppm/°C and

about 100ppm/°C.  When the metal includes aluminum (Al), the

liner material includes tungsten (W), the liner thickness

is in the range of between about 10nm and about 20nm, and

20    the CTE of the insulator is in the range of about 50ppm/°C

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an about 75ppm/°C. When the metal is aluminum (Al), the liner material includes tungsten (W), the liner thickness is in the range of between about 20nm and about 30nm, and the CTE of the insulator is in the range of between about

5      75ppm/°C and about 100ppm/°C.

Having described preferred embodiments for control of liner thickness for improving thermal cycle reliability (which are intended to be illustrative and not limiting), it is noted that modifications and variations can be made

10     by persons skilled in the art in light of the above teachings. It is therefore to be understood that changes may be made in the particular embodiments of the invention disclosed which are within the scope and spirit of the invention as outlined by the appended claims. Having thus

15     described the invention with the details and particularity required by the patent laws, what is claimed and desired protected by Letters Patent is set forth in the appended claims.

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